Modeling of Transient Regeneration Behavior
of
Incompletely Regenerated Gas Cleaning Filter Media

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Rigid ceramic filters are used for removing particulate matter from gas streams at high temperatures. As the particulate matter (dust cake) collects on the surface, the filtration pressure increases; to maintain economical operation the dust cake must be removed frequently by backpulse cleaning. Often, the dust cake is not completely removed by the backpulse pressure; this patchy cleaning will affect filter operation.

We have developed a fine-scale model of filter cleaning. In this model, the filter cake is gridded into imaginary (0.5 mm)^2 blocks; the model includes adhesive forces between the blocks of filter cake and the filter, as well as cohesive forces between the neighboring blocks of filter cake. Previous work on the model investigated the patchy cleaning during the first cleaning cycle and its dependence on filter cake thickness and applied pressure.

In this paper, we begin to study the way that patchy cleaning and subsequent filtration evolves from one cycle to the next (transient regeneration). Our simulations show that there are weakly bound regions, where the filter cake is removed during every cycle. Obviously, more strongly bound regions will be removed fewer times, if at all. More interestingly, there are regions where the filter cake is lifted up, but not removed during one cycle; many of these regions are removed during the next cycle. The evolution of patch size is also investigated. Our model enables a detailed quantitative investigation of the way that these various effects depend upon filter cake thickness, bonding forces and strength of the pressure pulse.

INTRODUCTION

Over the past six years, we have developed a fine-scale-model to study backpulse cleaning of ceramic filters.[1]-[5] The focus of this modeling effort has been to relate results for the cleaning (e.g. efficiency, size of cleaned fragments, patchiness, etc.) to controllable parameters of the real process (i.e. strength of pressure pulse, thickness of the cake, cohesive properties of the cake, etc.) with as few adjustable parameters as possible. In this work, we have studied aspects of the filter cleaning during one cycle: the effects that the cake thickness and the strength of the backpulse pressure have upon the cleaning efficiency, the spatial character of the patchy cleaning, and the size distribution of fragments removed. We found that increased cake thickness both improved cleaning efficiency at all but very low efficiencies ($f<0.2$, i.e. 20%) and increased the patch areas in patchy cleaning. In this paper, we extend our investigation to the cycle-to-cycle changes in patchy cleaning and subsequent filtration (transient regeneration).

In studying this transient regeneration, we need to re-deposit filter cake on the patchily cleaned filter before the next cleaning cycle. One advantage of modeling is the ease with which one can isolate one feature of the problem and study the effect of that one feature independent of all other features. Experimental investigations of transient regeneration have observed numerous uncleaned patches (places where the filter cake has not been removed) which were raised off the filter surface (adhesive bonds broken).[6] Because the interface between the lifted filter cake and the filter is largely shielded from the newly deposited filter cake, it seems unlikely that this cake will re-adhere to the filter with anything close to the former adhesive strength.

This study focuses on the effect that these broken (and un-repaired) adhesive bonds have upon the transient regeneration. We assume that during the subsequent filtration cycle, the newly deposited filter cake is identical to the filter cake at the beginning of the previous cycle in all respects except for these broken adhesive bonds. This is obviously incorrect in that the filtration pressure will not change from cycle-to-cycle. However, in this zeroth-order model, the effect of the damage caused by the broken/unrepaired bonds becomes the sole cause of all transients in the regeneration. If the broken bonds had been repaired, the re-deposited filter cake would be identical from one cycle to the next so that there work be no transient regeneration behavior.

In the study of fracture mechanics, it is well known that the buildup of stress at defects makes the defect structure of a material as important in determining the strength of that material as is the microscopic bonding between the constituents of the material.[7],[8] Therefore, these newly broken adhesive bonds will provide new defects which will make this cleaning significantly different from the previous cleaning. Of course, this model of filter deposition is not completely realistic. Notably, unlike the assumption of our model, the cake will not have uniform thickness after each filtration cycle. The cake will be thicker in the uncleaned regions because some new cake will be deposited in these regions, and the cake will not regain its original thickness in the cleaned regions; these effects will be included in a later version of our model.

In Section II, we briefly describe our filter cleaning model which has been fully presented elsewhere.[1],[2],[4] In section III, we present results from our model, which includes the effect of the broken/unrepaired bonds but not the changes in filter cake deposition from one filtration cycle to the next.

FINE-SCALE MODEL OF FILTER CAKE REMOVAL

In the physical system motivating this model, a layer of filter cake is deposited on a cylindrical candle filter to some thickness, t ; then a backpulse of compressed air is applied from the inside of the candle filter to blow-off the filter cake, thus cleaning the filter. The force actually responsible for removing the layer of filter cake is due to the pressure drop, ΔP, across the layer.

Fig. 1. The gridding of the filter cake around the cylinder. In the simplified planar model, continuity around the cylinder is preserved by periodic boundary conditions connecting the y=0 and y=L edges. The backpulse pressure force F causes displacements, ε, in the z direction.

We present a brief overview of our basic model, which has been fully described elsewhere.[1]-[5] In our model, the layer is gridded into rectangular blocks, of base ℓ^2 and height $T\ell$, connected to the filter and to each other by spring like forces. This applied backpulse pressure force, $F = \Delta P \ell^2$, will be balanced by the adhesive and cohesive spring forces (with spring constants k^a and k^c respectively). Equation 1 shows the force balance between the applied force F on a block at $\vec{r} = \frac{l}{2}(i,j)$ (i and j are even integers determining the location along the x and y directions, respectively) and the displacements of that block and the surrounding blocks:

$$F = k^a_{i,j}\,\varepsilon_{i,j} - \Big\{ k^c_{i-1,j}\,(\varepsilon_{i-2,j} - \varepsilon_{i,j}) + k^c_{i+1,j}\,(\varepsilon_{i+2,j} - \varepsilon_{i,j}) + k^c_{i,j-1}\,(\varepsilon_{i,j-2} - \varepsilon_{i,j}) + k^c_{i,j+1}\,(\varepsilon_{i,j+2} - \varepsilon_{i,j}) \Big\}. \qquad (1)$$

These spring constants are chosen randomly from particular probability distributions so that the average stiffness of the adhesive springs is 1/2 , and the average stiffness of the cohesive springs is T/2 ($\langle k^a \rangle = \frac{1}{2}$ and $\langle k^c \rangle = \frac{T}{2}$). This thickness parameter, T, gives the ratio of average cohesive to average adhesive force. [1]-[3]

Given the distributions of stiffnesses and the value of the force, F, we perform Gauss-Seidel iterations to determine the displacements. If any adhesive spring is stretched beyond its strength, S^a, i.e. that spring will break; similarly, if any cohesive spring is stretched beyond its strength, S^c, i.e.

$$k^a_{i,j}\varepsilon_{i,j} > S^a_{i,j} \quad \& \quad k^c_{i,j+1} \,|\varepsilon_{i,j} - \varepsilon_{i,j+2}| > S^c_{i,j+1} \qquad (2)$$

that cohesive spring will break. The strengths are chosen so that the strength of the adhesive springs is given by $\langle S^a \rangle = \frac{1}{2}$ and so that the average value of the strength of the cohesive springs is given by $\langle S^a \rangle = \frac{T}{2}$. This model is similar to many models of quasi-static, tensile fracturing in the scientific literature.[9]-[11]

RESULTS FOR TRANSIENT REGENERATION IN THE MODEL

Having deposited a layer to thickness T with the distribution of strengths and stiffnesses described in Secton II, we use our code to remove the layer with a pressure pulse

$$P(t) = P_{max} \ (1 - f(t)) \qquad (3)$$

where (1 - f(t)) is the fraction of the layer remaining at time t. Equation 3 assumes that the flow-velocity of the backpulse is nearly constant and that the pressure

Figure 2. Patchy cleaning cycles 9 (on left) and 10, in the transient regeneration of a model filter cake with thickness T=0.5. The black areas are uncleaned, the white dots represent broken adhesive bonds where the filter cake is lifted off the filter surface.

decreases proportional to the amount of filter cake removed. Although this assumption is simplistic [12], it yields reasonable time dependence for the pressure pulses.[5],[13],[14] Significantly improving the pressure pulse dependence would require realistic fluid dynamics as well as a dynamical filter-cake removal model which is far beyond the scope of our quasi-static model.

Figure 3. Patchy cleaning cycles 9 (left) and 10, in the transient regeneration of a model filter cake with thickness T=1.0 . The black areas are uncleaned, the white dots represent broken adhesive bonds where the filter cake is lifted off the filter surface. The cross-hatched rectangle near the bottom of the figure shows a region that, in cycle 9, is raised off the filter surface but uncleaned; in cycle 10, all of the region is removed excepting a part on the right, which had no nearby broken bonds in cycle 9.

Figures 2 and 3 show the patchy cleaning for cycle numbers 9 and 10 for two thicknesses. In these figures, approximately 60% of the filter cake has been removed (white regions); the white dots in the black regions show the locations where the filter cake was lifted (broken adhesive bonds). The effect of thickness on patch size is obvious, with larger patches for the larger thicknesses. Furthermore, the effect of the unrepaired defects in the lifted regions on cleaning in the following cycle is clear. For both thicknesses, but more dramatically for the larger thickness, one sees regions which are lifted in cycle 9 and which are cleaned in cycle 10, e.g. the cross-hatched rectangles in Fig. 3. Furthermore, there is an obvious tendency for regions which have been cleaned in cycle 9, to remain uncleaned in cycle 10, showing that the lack of adhesive defects improves overall adhesion, e.g. see the uppermost right hand corner in Fig. 3.

Figure 4 For thicknesses, T=0.5 (on the left) and T=1.0, these figures show the fraction of the layer of filter cake removed during n of the 10 cycles. The plot symbols (x) show the values for each of the five realizations; the solid line connects the values from averaging the five realizations.

Thus, regions, that have been cleaned in cycle n, are less likely to be cleaned in cycle n+1 ,and regions, that have been lifted but not cleaned in cycle n, are more likely to be cleaned in cycle n+1. These findings suggest that there will be an alternation with many regions cleaned every other cycle. One would expect this effect to be more significant for cleaning efficiencies closer to 50% than to either extreme. Cleaning efficiencies near 100% require that essentially all of the sites be cleaned every cycle. One would also expect this effect to be less significant in the limit of small cleaning efficiencies (e.g. $f < 20\%$) because very few of the sites are cleaned during any one cycle and the small pressures associated with low efficiencies would lift the filter cake in relatively few locations. One might also expect this effect to be less significant at small thicknesses, where smaller patches tend to break off so that broken adhesive bonds would only affect the removal of smaller areas of nearby filter cake. Figures 4a and 4b quantify these discussions; they show the fraction of the filter cake removed n times. For thickness T=1.0 and for pressures which remove $f \approx 60\%$ of the filter cake there is a clear peak around n=5, showing that 36% of the layer is removed 4, 5 or 6 times (about 12% each time); this quantifies the importance of 'alternating' removal for this case. There is also a peak at n=10 showing that 13% of the layer is removed every time. For thickness T=0.5, there is no corresponding peak near n=0.5; the dominant features occur at n=10 and at n=0: 32% is removed all ten times, and 12% of the layer is never removed.

CONCLUSIONS

We have extended our fine-scale model of backpulse filter cleaning to investigate the cycle-to-cycle changes in the filter cleaning. In this zeroth-order model of the filter cake re-deposition, we have assumed that those regions of filter cake which are lifted in one cleaning cycle do not re-adhere during the subsequent filtration cycle, presumably because of the shielding of the cake-filter interface from new deposition. In this zeroth-level model, we observe the same tendency of these damaged regions to be removed in the next cleaning cycle, as can be observed in experiment.[6] However, because this model assumes that the filter cake is redeposited to the same uniform thickness at the end of each cycle, it is impossible to account for the changes in filtration pressure that are observed in experiment.[15]-[17]

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